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Final Report on 'Turbulence Measurements for LES' Workshop

R.J. Adrian[1], C. Meneveau[2], R.D. Moser[1], and J. Riley[3]

[1] Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign;
[2] Department of Mechanical Engineering, The Johns Hopkins University;
[3] Department of Mechanical Engineering, University of Washington.

Abstract

This report describes important open issues in Large-Eddy Simulation (LES) of turbulent flows, and points to possible directions for new-generation experimental studies that can address the relevant questions. This report is an outgrowth of a one-and-a-half day workshop held in Chicago in October of 1999 that was funded by NSF, ONR, AFOSR, DARPA and LANL. It contains an introduction to LES and a description of what are currently felt to be the most important pacing items for future developments in LES. It summarizes the type of experimental information that is needed and the new experimental methods that can be brought to bear on the problem. It also proposes several flows that appear well suited to address the important issues identified.

1 Introduction

On October 4-5 of 1999, a workshop was held in Chicago to discuss the development of Large-Eddy Simulation (LES) of turbulence and the role that experimental data must play in this development. The workshop was jointly sponsored by John Foss at NSF, Tom Beutner at AFOSR, Amy Alving at DARPA, Candice Wark at ONR and Shiyi Chen at the Los Alamos National Laboratory. The authors of this report were asked to organize the workshop.

The sponsors and organizers undertook this event because there are a number of important issues that must be addressed in the development of LES, and these appear to require extensive experimental input. Furthermore, because of the unique features of LES, it seemed likely that obtaining the needed experimental data would require experiments specifically designed for the purpose. Thus, close collaboration between experimentalists and LES developers is needed. The workshop was organized to begin fostering such collaborations.

Thirty-six participants were invited to Chicago for a two-day discussion of LES and experiments. The participants were approximately evenly divided between experimentalists and computationalists, with the occasional theorist added for good measure. A list of participants appears in the appendix. The participants were limited to 36, though there were many others who were interested in attending, in order to foster effective discussions. Participants were selected to represent a wide range of experimental and computational interests and activities.

There were three immediate goals of the workshop:

- To have the LES and experimental turbulence research communities educate each other regarding what is required for progress in LES and what is possible given current and foreseeable experimental instrumentation.

- To identify promising experiments that could be undertaken to address LES development.
- To begin a discussion in the turbulence research community as a whole regarding the role of experiments in LES development.

The workshop consisted of two hours of introductory talks given by the organizers to provide background for the discussions. During most of the remainder of the meeting, the participants were divided into four groups for discussions of different aspects of the LES problem.

This document is the report of the results of the workshop. It is organized as follows: In section 2, fundamentals of LES are reviewed and important open issues are described on the basis of various phenomena occurring in flow over an airfoil. Section 3 summarizes the type of information needed for advancing LES, section 4 reviews the relevant instrumentation, and section 5 proposes several flow configurations that were discussed during the workshop. Concluding remarks are given in section 6.

2 Issues in LES and illustration in flow over airfoil

2.1 Introduction to LES

The technique of Large-Eddy Simulation (LES) has emerged as a very promising alternative to the traditional RANS approach in order to confront the scale-complexity problem inherent to high Reynolds number turbulent flows. For reviews of LES, see Rogallo & Moin 1984, Lesieur & Metais 1996, Piomelli 1999, and Meneveau & Katz 2000.

In LES, one separates the motion into small and large scales, and solves equations for the latter. The separation is achieved by means of a low-pass filter, which can be formulated in several ways, such as an integral filter, or a projection onto a finite set of basis functions. However, an extremely broad set of filters can be expressed as integral filters (including projection filters), so we will consider only integral filters here. In the simplest case of a homogeneous filter (i.e. a filter that is independent of location), the filter is applied by convolving the velocity $\mathbf{u}(\mathbf{x}, t)$ with the filter kernel $G_\Delta(\mathbf{x})$. The convolution kernel is devised to eliminate scales smaller than Δ. The LES equations are obtained by filtering the Navier-Stokes equations and read (for incompressible, nonreactive flow)

$$\partial_t \overline{\mathbf{u}} + \overline{\mathbf{u}} \cdot \nabla \overline{\mathbf{u}} = -\frac{1}{\rho} \nabla \overline{p} + \nu \nabla^2 \overline{\mathbf{u}} - \nabla \cdot \boldsymbol{\tau}, \qquad \nabla \cdot \overline{\mathbf{u}} = 0, \tag{1}$$

where $\overline{(\,)}$ represents a convolution with $G_\Delta(\mathbf{x})$, and $\boldsymbol{\tau}$ is the subgrid stress tensor. When the equations are written as in (1), $\boldsymbol{\tau}$ is given by

$$\tau_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j. \tag{2}$$

Equations 1 are amenable to numerical discretizations at a spatial resolution near Δ, which is typically much more affordable than Direct Numerical Simulation, which requires resolutions near the Kolmogorov scale, η. When the filter is not homogeneous, the subgrid term cannot be written as the divergence of the subgrid stress as in (2), because the filter operator does not then commute with differentiation. In general, for inhomogeneous filters, the divergence of the subgrid stress in (1) would be replaced by the subgrid force $\mathbf{m}$, which would include the effects of the noncommuting filter. However, these commutation effects are often ignored. The subgrid force is just the term that appears in the LES equations, which with homogeneouos filters is the divergence of the subgrid stress.

To close (1), τ_{ij} (or m_i) must be expressed in terms of the resolved (filtered) velocity field. In the absence of an accepted theory of turbulence to solve the problem of SGS modeling, the development and improvement of SGS models must include judicious use of empirical information. The main objective of this workshop is to explore what experimental turbulence research can contribute to this goal.

2.2 The Role of Experimental Data

Large-Eddy Simulation is a turbulence prediction technique, which like RANS (Reynolds Averaged Navier Stokes) relies on a model to account for the effects of turbulent fluctuations that are not explicitly simulated. The subject of the workshop reported on here was the need for experimental data to assist in the development of such models. However, if LES is to be a predictive tool, it must be applicable to new flows in the absence of such detailed, or indeed any experimental data on that flow. So, the models that are developed must be broadly applicable.

The need for experimental data extends to a broad range of flows, with various complicating features, such as walls, imposed strains and separations, and various complicating physics, such as scalar mixing, combustion and compressibility. These are needed because we want LES models that are applicable in flows with these features. The expectation is that well constructed models that work in idealized flows with these complications, will work in any flow with such complications. Since the model need account for only the small scales of turbulence, the prospects for such broad applicability are better than for RANS models which must account for all the turbulence fluctuations.

The data discussed here is needed for two purposes: the development of LES models and the validation of LES models. For model development, the data is needed for such things as setting constants, suggesting functional forms and dependencies and evaluating the causes of model shortcomings. In at least one modeling technique, detailed data is used directly to formulate the models (Langford & Moser 1999). To support model development, very detailed measurements that will allow the determination of the terms that are being modeled are most useful (see section 3). Such measurements are needed in a modest number of different flows that exhibit some or all of the complications discussed above. The task of the LES modeler will then be to use this information to construct generally applicable models. To validate these models, less detailed measurements are needed in many more flows. For validation, the required measurements are of the quantities we expect an LES to be able predict, and many more flows are needed to ensure that the are in fact valid over a broad range of flows.

The ultimate goal of all the measurements and model development is an LES model or set of models, with well characterized applicability, that can be used with confidence to predict the effects of turbulence in complex technologically relevant flows. An example application is discussed below.

2.3 Flow over airfoil

To illustrate some of the difficulties encountered in performing an LES in a relatively complex flow of technological importance, we consider the example of an airfoil, as sketched in Fig. 1. When performing LES of this flow at high Reynolds numbers, various difficulties arise that LES does not currently handle well. Near the leading edge, the incoming flow is subjected to very strong mean (irrotational) deformations. Incoming turbulence (part of which may be unresolved) will be strongly affected by this rapid distortion. Little is known at present about how well SGS models represent the response to such rapid perturbations (see e.g. Liu *et al.* 1999). On the suction side of the airfoil, the turbulent fluid continues along over a laminar boundary layer which is evolving toward a possible transition to turbulence. It is well-known that perturbations in the free-stream can strongly affect transition scenarios (Goldstein & Hultgren, 1989). If those perturbations occur at small scales (unresolved in LES), an LES will have great difficulty correctly predicting transition. Also, at high Reynolds number it is often not possible to resolve the laminar boundary layer, and the prediction of transition in an LES is an open problem. A related problem is how to prescribe inflow and outflow conditions in LES (see e.g. Lund *et al.* 1998).

After transition, at high Reynolds numbers it becomes impossible to resolve the near-wall features of the boundary layer such as the viscous sublayer on the LES mesh. This introduces severe challenges to LES modeling. One such challenge is that the dynamically important "large-scale" turbulence is not resolved

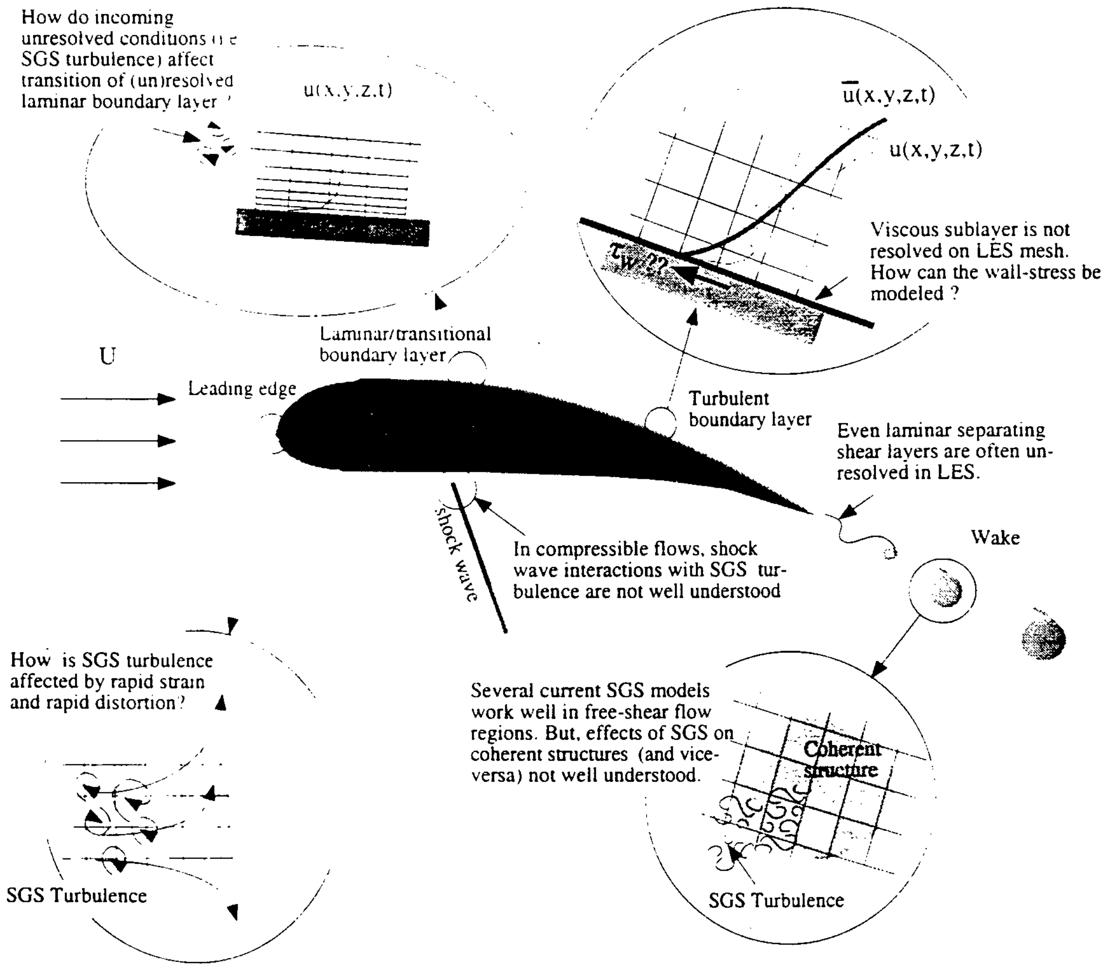

Figure 1: Sketch of flow over airfoil and various challenging regions for LES.

near the wall. Another is that the wall-shear stress cannot be related to the resolved velocity by means of differentiation of the velocity at the wall. Classical models of the wall-shear stress τ_w such as those often used in LES of atmospheric flows relate τ_w to the resolved velocity in the log-layer using an assumed log-layer behavior. For general, unsteady conditions with pressure gradient and roughness effects, the problem remains a challenging one. For a discussion, see the recent review article by Piomelli (1999).

As the boundary layer evolves further, it may separate. The region around the separation point presents further challenges for near-wall modeling, because of the strong stream-wise inhomogeneity. But, once the flow has separated, the free-shear wake region is characterized by turbulence that is approximately in equilibrium. Here a number of current SGS models perform fairly well in reproducing mean velocities and second-order statistics. However, not much is known about the ability of current models to reproduce details of coherent structures typically found in such flow regions.

Compressibility effects play an important role in high-speed aerodynamics. Very often the relevant physics occur at small scales that cannot be resolved on the LES grid (e.g., shock waves and their interaction with turbulence, Knight and Degrez 1998). Furthermore, it is not clear that present models can be accurately extended to flows with large density differences. Other subgrid physics that pose serious challenges to LES (not covered in the example of Figure 1) include: turbulent reacting flows, where generally the entire reaction occurs at the subgrid scales and, hence, requires modeling (e.g., Cook and Riley 1998; Colucci et al. 1998);

two-phase flows, where usually the interactions between the two phases take place at the subgrid scales; rotating flows, where the effects of rotation can be either stabilizing or destabilizing at the subgrid scales (e.g., Piomelli and Liu 1995); and stable or unstable density stratification, which can significantly alter the transfer of energy to the subgrid scales, and hence their modeling (e.g., Métais and Lesieur 1992).

Finally, the example of flow over an airfoil illustrates the severe challenges to numerical techniques posed by turbulence simulation in complex-geometry flows. Turbulence simulations (both LES and DNS) are commonly carried out in very simple geometries with highly accurate, low dispersion, low (or no) dissipation numerical methods. This is necessary because of the broad range of scales that need to be simulated (even in LES) and, for LES, in order to minimize the effects of discretization error on SGS models. These methods are often not applicable to more complex geometries. Thus, the airfoil application requires further development of highly accurate low dispersion methods that can be used with local grid-refinement and on unstructured grids etc.

2.4 Pacing items for LES and main issues addressed during the workshop

The foregoing discussion illustrates what are considered to be the main pacing items for the successful deployment of LES to predict high Reynolds number complex flows in practically relevant conditions. They are

- Realistic parameterization of the SGS stress tensor (or the subgrid force) under a variety of non-ideal conditions (such as non-equilibrium turbulence, transitional flows, effects of coherent structures, etc.).
- Appropriate specification of inlet and outlet conditions, and the effects of these conditions on transition mechanisms.
- Modeling near-wall effects and wall stress in high-Reynolds number wall-bounded flows in which the near-wall features (e.g. viscous sublayer, buffer layer, streaks etc.) cannot be resolved on practical LES meshes.
- Modeling unresolved physics such as compressibility effects, chemical reactions, effects of other phases such as particles, droplets and bubbles, etc.
- Continued improvement of numerical techniques, and formulation of SGS models that account for numerical discretizations errors.

Physical experiments can help to address the first four of the items listed above, which thus form the focus of interest of the workshop.

3 Types of information needed

In considering the experimental information needed for LES development and validation, it is important to keep in mind the unique properties of LES. As in RANS modeling, LES is in need of information about the quantities for which models are being developed, and information about quantities that are to be predicted. The former is for model development (*a priori* analysis, see section 3.2), the latter is for validation (*a posteriori* analysis, see section 3.1). The nature of LES makes these quantities significantly more complicated to measure and understand. Some of the complications involved in producing experimental data for LES are listed below.

1. In LES, both the terms to be modeled and the quantities to be predicted are defined by the filter that is used to distinguish large scales from small scales. Thus, to be most useful for LES, experimental data (e.g. velocities) need to be filter-able. Since the filters used in LES are generally spatial filters, to the extent possible, the experimental data needs to be spatially resolved, so that spatial filters can be applied.

2. LES should be able to predict more than just one-point statistics. In fact, ideally an LES should be able to recover any multi-point also statistical measure of the filtered velocity. Thus, there is a great need for multi-point statistics from experimental data, especially well-resolved two-point spatial correlations.

3. LES is designed to simulate the evolution (dynamics) of the large-scale turbulence. Thus, time-evolution information is required. We need to know how the large scales evolve; however, turbulence is chaotic so long-time evolution is not predictable. Evolution over short-times (or time derivatives) is thus of primary interest.

4. Since the LES simulates the dynamic large-scale turbulence, information about the dynamic large-scale turbulence is needed at the inflow boundaries of a simulation domain. This is unlike RANS, where one only needs to know the statistical RANS state variables at the inlet. Thus, to ensure that a simulation in a finite domain and an experiment are working with the same turbulence, an experiment would need to provide enough time-resolved data on an inlet plane to allow the in-plane space and time variation of the velocities to be inferred. Obtaining such data is potentially extremely difficult, see section 3.5 for details.

5. Exactly what quantities are needed for an LES study and how they are filtered depends on the particulars of the LES formulation being studied. That is, in general, it depends on the filter and the approximations made when writing down the LES equations. As a result, it will likely be most effective to measure and retain the unprocessed velocity data, which can then be filtered and used to compute any quantity of interest. This also suggests that it will be extremely important for LES modelers/simulators to work closely with experimentalists in producing and analyzing the data.

A brief discussion of the uses made of experimental and DNS data in LES development follows. To simplify, the discussion below is based on LES of incompressible, nonreacting single-phase flow, except where noted.

3.1 A-posteriori Analysis

To evaluate the performance of a model for the SGS stress, $\tau_{ij}^{\mathrm{mod}}(\mathbf{x}, t)$ or for the subgrid force, the results from a simulation that uses the model are compared to available data. The data can be obtained from direct numerical simulation (DNS) or from experiments, typically in the form of mean velocity and Reynolds-stress distributions, spectra, etc.. Piomelli et al (1988) has coined the name 'a-posteriori tests' for such comparisons to emphasize that the model is evaluated only after it has been implemented in a simulation.

One important issue, often neglected in a-posteriori analysis, is the need for explicit filtering of the experimental data. LES gives results for the resolved velocity field, $\overline{u}_i$, whereas most experimental data are for the unfiltered velocity field, u_i (Of course experimental resolution always causes some kind of filtering of the data, e.g. at the measurement volume, but for the sake of this discussion we assume that this volume is significantly smaller that Δ). Typically, experimentally obtained root-mean-square (rms) values of velocity differ from LES results not only due to errors in SGS modeling, *but also because the LES results often do not include the contributions from the SGS turbulence.* For SGS models that do not provide explicit predictions of this contribution (e.g. with the Smagorinsky model, the SGS kinetic energy is not predicted, and hence cannot be used to supplement velocity rms values), a meaningful comparison between LES results and experimental data should involve filtering of the latter.

In the case of isotropic turbulence, this can be achieved by exploiting isotropy and performing the filtering as a post-processing step on the measured energy spectrum. This has been the practice in simulations of decaying isotropic turbulence that are compared with the classical grid decay experiments of Comte-Bellot & Corrsin (1966). In the latter, longitudinal spectra measured at various downstream locations are transformed into 3-D radial spectra using isotropy. They are then filtered and integrated to yield the decaying rms values of filtered turbulence which can be directly compared to LES (see e.g. Moin *et al.* 1991, Meneveau *et al.* 1996, Misra & Pullin 1997). Filtered energy spectra can also be compared. However, in flows where the SGS turbulence is not isotropic, this procedure cannot be applied since the longitudinal spectrum is not uniquely related to the 3-D spectrum. Similar difficulties arise in non-homogeneous flows, for which comparisons of LES with experimental data are especially needed. For instance, in Kravchenko & Moin (1998) temporal LES spectra in the cylinder wake are compared with experimental hot-wire data of Ong & Wallace (1996). The comparison would have been more conclusive if the experimental data could have been spatially filtered.

If one is interested in second-order statistics only, a suitable generalization of the spectral approach to non-homogeneous flows is to perform measurements of all relevant two-point correlations. These can then be processed by convolution to yield correlation functions of the filtered velocity field. This approach has the advantage that the filter scale and kernel can be changed during post-processing (see the discussion in Jimenez & Moser (1998)). Extending this technique to higher order statistics quickly becomes unmanageable. For example, to compute filtered third order statistics, three-point third-order correlations are required. Similarly to determine the probability distributions (pdf's) of the filtered fields, one needs to know the multi-point joint pdf's.

Because many different filters are possible and of interest, the most useful data for LES, though perhaps most difficult to obtain, are unaveraged spatially resolved (at least locally) instantaneous velocity (and pressure, density, etc. for compressible flows). These data can then be filtered and averaged as needed to obtain the statistical quantities of interest.

However, obtaining experimental data that can be spatially filtered is quite difficult (see section 4). In situations in which this is not possible, there are less desirable alternatives, which can none-the-less produce useful information. One example is the direct measurement of spatially filtered velocities with some specific filter, at some particular scale, as was done by Cerutti & Meneveau (2000). They used data from an array of hot-wires to approximate a 2-D box filter (see also section 4.2, and high-order moments of such filtered velocity were reported. Evidently such data could also be produced with massive planar PIV (see section 4.3). This approach is limited since, according to the preceding discussion, the results cannot be filtered with another filter during post-processing. Hence, the Cerutti & Meneveau data are only relevant for a box filter at the scale used in the experiment. On the other hand, such data can be compared to simulation results from LES performed with better resolution Δ' (with $\Delta' << \Delta$) which is then filtered according to the filter that is used in the experimental setup (e.g. a 2-D box-filter). Such comparisons of the statistics of the larger resolved scales can add significant information during *a-posteriori* tests.

A-posteriori tests are considered to be the ultimate test of model performance. However, due to the integrated nature of the results (combining effects of numerical discretizations, time integration, and averaging), *a-posteriori* tests typically do not provide much insight into the detailed physics of models, and the reasons why they do, or do not work.

3.2 A-priori Analysis

To obtain more insight into the workings and failings of LES models, one can directly compare modeled quantities such as the subgrid stress $\tau_{ij}(\mathbf{x}, t)$ and its measured value. Such a comparison requires data at high spatial resolution that is sufficient to resolve the subgrid scale. The modeled quantity (e.g. $\tau_{ij}(\mathbf{x},t)$) is evaluated according to its definition (2) and the model is evaluated based on the filtered data. For such analysis, Piomelli *et al.* (1988) coined the name 'a-priori test' to emphasize that no actual LES is involved. The data for such studies can be generated using DNS, which allows processing the full three-dimensional velocity field, but is limited to low Reynolds numbers and simple geometries. Examples of a-priori tests based on DNS can be found in Clark *et al.* (1977), McMillan & Ferziger (1980) and Bardina *et al.* (1980), Piomelli *et al.* (1991), Domaradzki *et al.* (1993), and Härtel *et al.* (1994). Further, such *a priori* analysis can be used to directly formulate LES models (Langfrod & Moser, 1999). The term "*a priori* analysis" is used rather than "*a priori* test" because, in this case, testing is not the primary goal.

An alternative that complements DNS is to use experimental data. Experiments provide access to high Reynolds number flows but, with limitations, since generally only partial information is available, such as a subset of all the relevant fields can be measured.

A-priori analyses have been performed from two points of view.

- One is a very detailed point of view in which the real stress field, τ_{ij}, and the modeled one, $\tau_{ij}^{\rm mod}$, are considered on a point-wise basis in individual realizations. In this analysis, the model is evaluated based on the filtered real turbulence, as if the filtered real turbulence were an LES field. Historically, comparisons of this sort have been carried out using correlation coefficients between τ_{ij} and $\tau_{ij}^{\rm mod}$, their divergences (SGS force) or their contractions with the strain-rate tensor (SGS dissipation) (Clark *et al.* 1977). They can also be compared based on the mean square error between them, especially the SGS force (Adrian 1990, Liu *et al.* 1999, Langford & Moser 1999). The latter appears to be a more stringent criterion as even variables that are well correlated can have a large square error if their mean or rms values differ (Liu *et al.* 1999).

  Since the small-scale fields are essentially stochastic, even for a given fixed large-scale field, pointwise comparisons are expected to lead to large differences between real and modeled stress fields. Indeed, there is a lower bound on the possible root-mean-square difference between real and modeled subgrid force. This lower bound could be quite large, of the same order as the subgrid force itself (Langford & Moser, 1999). It is extremely difficult to determine precisely what this lower bound is, and this makes interpreting pointwise *a priori* comparisons difficult.

  The fact that there can be large differences between modeled and real subgrid terms does not mean that the models and the LES based on them are poor. Indeed, it can be shown (Pope, 1999; Langford & Moser 1999) that if the model attains the minimum possible mean-square difference with the real term, then this is sufficient for the LES to reproduce the statistics of the simulated large scales. The unique model that attains this minimum is the conditional average of the subgrid term given the large-scale velocity field. This observation leads to a strategy for LES development in which the conditional average (the ideal model) is approximated directly (it cannot be determined exactly).

  One technique for approximating the ideal model is stochastic estimation (Adrian 1977), in which one determines a linear (or higher order) estimate of the conditional expectation of the subgrid force. Such estimates demand large quantities of data. Particularly, the two-point correlation of the subgrid force with the velocities (or other estimation variables), as well as two point correlations of the velocities (or other variables) with themselves.

- The second point of view is concerned with important statistical features of the subgrid stress or force, and how well they are represented by the model (see Meneveau (1994) for a discussion on statistically necessary conditions for LES models). For instance, if one wishes to examine the effects of the SGS on the mean momentum equation, one might compare the mean SGS stress $\langle\tau_{ij}\rangle$ with the mean of the modeled SGS stress $\left\langle\tau_{ij}^{\rm mod}\right\rangle$. These quantities are important, especially when the grid or filter scale

Δ is comparable to the turbulence's integral scale. Then the mean SGS stress is comparable to the Reynolds stresses and they affect mean momentum directly. This occurs often in LES of wall-bounded turbulence, or turbulence with other strong inhomogeneities.

Analysis of the resolved or unresolved kinetic energy equation (Piomelli *et al.* 1991) shows that it is strongly affected by the SGS dissipation rate $-\left\langle \tau_{ij}\overline{S}_{ij}\right\rangle$. Hence one wishes a model to reproduce this statistical feature of the SGS stress. That is to say, a good model should enforce that

$$-\left\langle \tau_{ij}\overline{S}_{ij}\right\rangle = -\left\langle \tau_{ij}^{\mathrm{mod}}\overline{S}_{ij}\right\rangle . \tag{3}$$

If for instance the SGS dissipation is under-predicted by a model, there will be pile-up of resolved kinetic energy and excessive resolved Reynolds stresses may result. In that case, the mean velocity will be affected by excessive turbulent transport. Overly dissipative SGS models may dampen resolved turbulence too much, again affecting resolved Reynolds stresses which will affect the mean velocity field.

The results of Langford & Moser (1999) provide strong evidence for the importance of modeling the SGS dissipation. In isotropic turbulence, with Fourier cutoff filters, they observed that a linear estimation model, which by construction matches the per wavenumber dissipation rate, but no other statistical properties of the model, captures the dominant effect of the SGS stress term. Further, *a posteriori* tests show that this simple linear model performs very well (Moser, Langford & Volker, 1999).

Much can be learned from conditional averaging in more complex flows. For instance, one is often interested in coherent structures computed from LES. It is important that the SGS model dissipate resolved kinetic energy properly with respect to the coherent structure. For instance, one would not wish to dissipate excessively inside the core of large-scale coherent vortices. Many methods of identifying and defining coherent structures exist in the literature, one of which is conditional averaging. In this case it appears important that a model predict the correct conditionally averaged SGS dissipation,

$$-\left\langle \tau_{ij}\overline{S}_{ij} \mid \mathrm{cond}\right\rangle = -\left\langle \tau_{ij}^{\mathrm{mod}}\overline{S}_{ij} \mid \mathrm{cond}\right\rangle . \tag{4}$$

where 'cond' is some particular condition that is satisfied. This is consistent with the expression of the ideal model discussed above as a conditional average. Such analysis is described in O'Neil & Meneveau (1997) and Porté-Agel et al. (1998,2000). Conversely, the conditional velocity structure associated with certain SGS dissipation values can also be studied, see Piomelli *et al.* (1996) and Lin (1999). These studies have shown very strong effects of coherent structures upon SGS dissipation.

3.3 Additional Requirements for Compressible and Reacting Flows

When considering chemically-reacting flows, additional information is required of the models. For example, for non-premixed, chemically-reacting flows, in addition to the subgrid stresses mentioned above, also required (at a minimum) are the filtered values of a conserved scalar field (Z, the mixture fraction), its variance, and its dissipation rate (χ) (Cook and Riley 1998). Furthermore, since the reaction zone is usually fairly local, and the mixing/chemical reaction process is strongly nonlinear, it is probably the case that maintaining $\langle\chi^{mod}\rangle = \langle\chi\rangle$ will not be sufficient to correctly model even the mean reaction rate.

Information about the frequency distribution (filtered density function) of Z in a subgrid volume element is also necessary (Cook and Riley 1994). For models which solve the equation for the joint filtered density function of the species mass fractions, additional measurements are required for the filtered density, for the filtered velocity, conditional on the values of the mass fractions, and for the conditional species dissipation rates (Colucci *et al.* 1998).

For flows with large density variations, e.g., reacting flows or high-speed, compressible flows, it is convenient to introduce density-weighted filtering. Therefore, in order to test models, it is important to have measurements of the density field simultaneously with the other variables.

3.4 Wall Boundary Conditions

LES of wall-bounded flows at high Reynolds number present special challenges because the energy containing scales of turbulence will become small compared to any fixed grid or filter as the Reynolds number increases. It is desirable for the cost of an LES simulation to remain finite as the Reynolds number becomes infinite. In this case, at high Reynolds number, none of the familiar near-wall structure of wall bounded turbulence (e.g. viscous and buffer layers, streaks, inclined/hairpin vortices etc.) will be part of the simulated large scales. For example, if one is performing a channel LES say, with filter scales (grid scales) of 0.05δ (δ is the 1/2 width) then at $Re_\tau = 10,000$, the grid size is 500 wall units. This means that the closest grid point to the wall is at $y^+ = 500$, far out in the log layer, and this increases with Reynolds number. The LES wall boundary condition problem is then to account for the effects of the near-wall turbulence between the wall and the first grid point, and its transfer of momentum to the wall. These observations indicate that detailed measurements throughout the log-layer are needed, since it is in the log layer, where both inner and out scalings are valid, that the closest grid point must be located, and it is the momentum transfer through the log-layer to the wall that must be modeled. Particularly useful will be two-point correlations and the other detailed data discussed in section 3.6.

In many formulations of the LES wall boundary problem, the fluctuating wall shear stress is the quantity that needs to be modeled. Thus wall shear stress data are of importance, and wall shear stress measured simultaneously with the velocity in a plane located at an appropriate location for the first grid point from the wall is even better. Another approach is to consider the boundary of the simulation to be at the first grid point from the wall. There one needs to specify the mean velocity tangential to the wall, as well as the turbulent velocity. Specifying the latter poses challenges similar to those of prescribing turbulence inflow conditions, discussed below.

3.5 Turbulent Inflow Characterization

Virtually all simulations will be performed in a finite spatial domain so that, at one or more of the boundaries of the domain, there will be an inflow, and this inflow is likely to be turbulent. Some specification of the inflow turbulence is then required. If such a simulation is to be compared to an experiment, then the inflow turbulence specified in the simulation must be consistent with the turbulence that exists in the experiment. Thus, detailed experimental information on a plane that could be used as an inflow boundary in a simulation is needed. How much data and how much detail are needed is not clear at this point, and it is likely to depend on the flow under consideration. Several examples of data that could be made available, and how useful they might be, are given below:

1. If all three velocity components are known on a plane as a function of time, then this is clearly sufficient data to specify the inlet turbulence for a simulation. However, this would be exceptionally difficult data to obtain from an experiment.

2. If one had a statistical description of the turbulence on the inlet plane (e.g. mean, Reynolds stress tensor, two-point space-time correlation) one could construct a stochastic inlet condition that matched these statistics. However, it is not clear how much statistical information is needed to assure that the simulated turbulence is consistent with that in the experiment. This sort of inlet has been used in the past (Le & Moin, 1994; Lee *et al.* 1997) by matching mean Reynolds stress and/or spectra, and an adjustment region in which the turbulence heals from the artificial inlet condition occurred in these

cases. It seems likely that more detailed statistical properties would need to be matched, such as the Eulerian time correlations, or space-time correlations.

3. Intermediate between these two cases is to construct an inlet condition that matches both statistical information and the velocity time evolution at a small number of points. This has been done by Bonnet (Bonnet *et al.* 1997) using two-point correlation data to form stochastic estimates of the velocity on the inlet plane based on time records of velocity at several points. This was quite successful in the mixing layers studied by Bonnet, but it is not clear how many points of velocity data would be needed for other flows.

3.6 Qualities of an Experiment for LES

To satisfy the needs outlined above, an ideal experiment would provide spatially resolved velocity measurements in as high a dimension as possible (2 or 3). The measurements would be resolved in time, for at least a short duration, to allow estimation of time derivatives, and would have at least two decades of spatial dynamic range (preferably more), so that filters could sensibly be applied. Ideally, for inflow characterization, time-resolved measurements of all three velocity components on a suitable inlet plane would be provided, though detailed statistical information (including two-point correlations) in the plane along with simultaneous time records of velocity at an array of points on the plane could also be useful. For maximum flexibility, the unprocessed velocity data would be made available, perhaps in addition to precomputed statistics. Also of interest are two-point correlations, both to allow computation of filtered statistics (Jimenez & Moser 1998), and to use in model development as described by Langford & Moser (1999). Finally, in wall bounded flows, time and space resolved measurements of wall shear stress would be available. Current techniques do not easily allow for such measurements, although MEMS technology has promise toward this goal.

4 Experimental methods available

A large number of experimental techniques have been developed and used for the study of turbulence. In this section, the prospects for using these experimental methods to support LES development are discussed.

4.1 Previous experimental tools used for study of SGS in turbulence

Over the last several years, a variety of experiments and experimental data have been used for LES development, particularly for *a priori* testing. A brief summary of the existing literature on the experimental methods that have been used to date for a-priori testing is given by Meneveau & Katz (2000). Their summary reads as follows:

> Using planar Particle Image Velocimetry (PIV), 2-D distributions of four tensor elements can be measured by means of spatial filtering in two directions (see Liu *et al.* (1994, 1995), Meneveau & Katz (1999a) for data in the far-field of a round jet, Bastiaans *et al.* (1998) for results in free convection, and Liu *et al.* (1999) and Meneveau & Katz (1999b) for rapidly distorted turbulence). Laser-Induced-Fluorescence concentration measurements (Dahm *et al.* 1991) have been used to measure the subgrid-scale variance of a conserved scalar (Cook & Riley 1994). Using hot-wire single-point sensors, Meneveau (1994) as well as Meneveau & O'Neil (1994) studied grid turbulence and O'Neil & Meneveau (1997) considered turbulence in a cylinder wake. Porté-Agel *et al.* (1998) studied turbulence and scalar transport in the atmospheric boundary layer using a sonic anemometer. These single-point data were analyzed using temporal filtering,

which was interpreted as one-dimensional spatial filtering in the streamwise direction by invoking the Taylor hypothesis. To achieve quantitatively more accurate results, two-dimensional filtering should be used. It can be approximated by an array of point-sensors arranged along a line perpendicular to the mean velocity. This approach has been proposed by Tong *et al.* (1998) and applied in Porté-Agel *et al.* (2000a,b) for sonic anemometer measurements in the atmospheric boundary layer. It has also been applied to hot-wire measurements in laboratory turbulence (Cerutti & Meneveau, 2000, Cerutti *et al.* 2000). The accuracy of 2-D filtering and Taylor's hypothesis has been addressed for wall-bounded flows using DNS (Murray *et al.* 1996) and LES (Tong *et al.* 1998). Finally, techniques for multipoint three-dimensional velocity measurements, e.g. holographic PIV (Barnhart *et al.* 1994, Meng & Hussain 1995 and Zhang *et al.* 1997), are beginning to provide crucial data on the spatial distribution of all the SGS tensor components (Tao *et al.* 2000).

More detailed discussions of the various measurement techniques are given below.

4.2 Single-Point Instruments

Traditional methods of experimental fluid mechanics used instruments that measure quantities at a single-point, i.e., hot wires, hot films, laser Doppler velocimeter, pitot tube, concentration probes, etc. In the study of turbulence structure these instruments provide information on conventional single-point statistics, but their use in the general LES context is less straight-forward.

Known instruments inherently average in at least one dimension. For example, the hot wire averages along the length of the wire; LDV averages throughout the measurement volume, principally in the long direction of the measurement volume, and so on. If this averaging were consistent with the filter in a particular LES, then the instrument would provide a direct measurement of filtered velocity. However, this is unlikely to be the case, given the idiosyncratic averaging implicit in these instruments. Instead, the averaging length scale should be much smaller than anticipated LES filter scales, and the data should be filterable. Unfortunately, single-point probe data are only directly filterable in time, which can be considered a one-dimensional spatial filter through Taylor's hypothesis.

To enable true spatial filtering, multiple single-point probes are needed. Arrays of hot wire probes are currently used to obtain better data on the structure of turbulence, especially of larger eddies.

For filtering purposes, one needs measurements with probe separations significantly smaller than the filter width. Depending on the filter size and the accuracy with which the filter is to be represented, this can require an array with very finely spaced probes. For example, in a shear layer (e.g. channel or boundary layer), a filter width (in the cross-stream direction) of approximately 1/20 of the shear layer width would be typical. Probe separations would then need to be at most 1/10 of this filter width to represent the integral implicit in the filter definition. For a typical laboratory shear layer width of order a centimeter, probe separations would need to be of order 50 microns.

Such small separations would be needed to obtain accurate estimates of filtered quantities. However, when such fine probe separations are not possible, useful information can still be obtained. Often the subgrid fluxes are dominated by the largest of the unresolved scales. In such cases, approximations to the filtered quantities could be measured using coarser probe separations (Cerutti & Meneveau 2000). This is not unlike the situation of Reynolds stresses which are dominated by the most energetic large scales and thus need not be measured at very high spatial resolution (e.g. compared to the Kolmogorov scale). Clearly, the uncertainties introduced by imperfect resolution of the filter operator using such probe arrays must be carefully quantified for each application.

Arrays of point sensors have also been used to study SGS fluxes and models in the atmospheric surface layer, based on arrays of sonic anemometers (see Tong *et al.* 1999 and Porté-Agel *et al.* 2000a,b). Sonic anemometers also measure temperature so that, in addition to SGS stresses, the SGS heat fluxes can be evaluated. While appropriate for the relatively large scales in atmospheric turbulence, the spatial and temporal resolution of sonic anemometers is not adequate for laboratory flows.

An alternative to arrays of multiple probes is to use a smaller number of independently movable probes and scan them to measure multi-point correlations. Again, one needs to bring the probe volumes close enough together (much closer than the LES filter length scale, such close proximity is usually prohibited by probe interference) to allow the correlations to be filtered. These multi-point measurements are made less daunting by the fact that only relatively small separation correlations are required to support filtering as described by Jimenez & Moser (1998) or modeling estimation analysis as described by Langford & Moser (1999). In either analysis, only separations up to several times the LES filter width are required.

The need for this type of multi-point information leads to increased emphasis on the development of multi-point measurement techniques which are able to make measurements at thousands of points at a single instant in time. The mainstream methods here are particle tracking velocimetry, particle image velocimetry and planar laser induced fluorescence; but, there are other less commonly used techniques such as Doppler global velocimetry, photochromic molecular tagging velocimetry and laser speckle velocimetry.

4.3 Planar PIV

multiresolution..

Particle Image Velocimetry (PIV) has become a widely used tool in fluid mechanics research, and it offers several interesting possibilities for measuring flow fields in the context of the study of large-eddy simulation. These methods offer three major capabilities that cannot be easily achieved with single point probes:

1. Simultaneous observation of large scales and small scales.
2. Data that is filterable in two and three dimensions
3. Measurement of multi-point statistics is feasible.

To appreciate the last point, consider as an example measuring the two-point correlation of an inhomogeneous flow on a 100×100 grid using a pair of movable probes. There are order 10^8 probe positions, and order 10^4 samples in time must be taken at each probe positions. For three-point statistics, it is worse since there are approximately 10^{12} sets of probe positions. In contrast, using a multipoint technique such as PIV, a sequence of measured (2D) fields allows all the multi-point statistics of interest to be computed.

A typical PIV system measures velocities in the plane of a laser light sheet over an area of roughly 100 millimeters x 100 millimeters with a resolution of approximately 1 millimeter, i.e., a grid of 100 x 100 velocity vectors are measured at an instant. The PIV can be made to measure over larger or smaller regions, but more than a factor of ten larger or smaller requires special steps. For example, to increase the field of view by a factor of ten requires increasing the laser power by a factor of ten, if the intensity of illumination is to be maintained. The limits of resolution of PIV have been tested recently in the development of micro PIV systems which are capable of resolving vectors on a micron length scale. However the field-of-view is correspondingly small. Time resolution is also an issue, especially for characterizing a turbulent inflow. In a PIV system, the rate at which velocity planes can be measured is limited by the rate at which the illuminating laser can be fired.

¿From the viewpoint of turbulence research, what is more important is the spatial dynamic range of the PIV system, which is the largest dimension that can be measured divided by the smallest dimension. Typically the range is of order 100:1. Larger dynamic ranges can be achieved but they require a special techniques such as the use of large format photographic film or special lenses. The biggest problem is simply that of recording enough information on the optical recording medium. Improving dynamic range requires increasing the information recorded on the medium. Since some media such as digital video cameras may already be nearly saturated, this means either increasing their size or using a different medium.

In PIV systems, the correlation analysis used to extract velocity vector measurements from the images yields a volume average of the continuous velocity vector field. If this volume average can be made to correspond to an LES filter, then direct measurements of filtered velocity are obtained. This may be possible because there is a potential to manipulate the averaging properties by adjusting the correlation algorithm and the properties of the light sheet. However, as discussed in section 3.6, it is more generally useful to provide data that can be filtered during later analysis. For this reason, it will generally be more desirable to adjust the PIV system to provide resolution that is much finer than probable filter scales, while providing a field of view that spans many filter scales. The 100:1 dynamic range of standard PIV is adequate for this purpose, provided the filter width falls approximately in the middle of this range. As summarized in section 4.1, this is the approach followed in Liu *et al.* (1994,1995,1999) and Bastiaan *et al.* (1999).

Planar light sheet PIV can measure two-dimensional vectors in the planar light sheet or, by means of stereo techniques, it can measure three-component vectors. Imaging over volumes is possible by scanning the light sheet, but the rate at which data can be recorded limits the rate of scanning to values that are too slow to be of practical interest for high Reynolds number turbulence. *Particle tracking velocimetry*, especially the photogrammetric variety, uses several cameras to triangulate the position of individual particles. It is also capable of measuring in three-dimensional volumes, but these techniques are limited to about 1000 to 3000 flow vectors. This represents a cube of no more than 15^3 vectors. The resolution is hardly enough to distinguish between large scales and small scales. Therefore, attempts to measure three-dimensional vectors in volumes have gone in the direction of holographic imaging, which has higher information recording capacity than photographic or videographic recording.

4.4 3-D Holographic PIV

In holographic particle imaging velocimetry one records the images of a cloud of light scattering particles using holographic methods. The images are recorded at two separate times and various methods, including more or less conventional PIV interrogation analysis, can be used to extract three-dimensional vectors throughout the volume of the cloud of particles. For descriptions of existing systems and preliminary results, see Barnhart *et al.* (1994), Meng & Hussain (1995) and Zhang *et al.* (1997).

In principle, full 3-D velocity fields allow measurement of the six independent components of the SGS stress tensor using 3-D filtering, and also the full velocity gradient tensor, if the resolution is adequate to evaluate derivatives. The errors in evaluating derivatives of velocity over distances equal to the vector spacing are typically still quite large. However, derivatives of velocity filtered over a number of vector spacings (e.g. to evaluate terms of current SGS models that depend on the filtered strain-rate tensor) can be evaluated with sufficiently small errors (for a recent study of 3-D alignments between SGS stress and filtered strain-rate eigenvectors, see Tao *et al.*, 2000).

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While of great usefulness, HPIV results obtained so far have been hard won. The systems are not very flexible and they are difficult and expensive to operate. Therefore holographic PIV in its current state does not offer a solution that one can expect, for now, to be widely used for turbulence research. There are several technological developments on the horizon that promise to improve HPIV capabilities (J. Katz, personal communication). These include development of digital reconstruction methods, continuing improvements in digital camera resolution and ongoing advancement in computational capabilities. It is to be hoped that this and other future developments in HPIV will make it a more widely applicable and robust diagnostic tool for turbulence research.

5 Suggested experiments to address pressing needs in LES

The participants of the workshop were divided into four working groups, with the charge of proposing specific flow conditions and experimental procedures that would best advance LES modeling. These groups were:

- Group A: Subgrid modeling in canonical incompressible flows.
- Group B: Specification of and sensitivity to inlet, wall-boundary, and initial conditions.
- Group C: LES in high-Reynolds number flows, especially wall-bounded flows.
- Group D: Treating "extra" subgrid physics, such as chemical reactions, compressibility.

Below, the conclusions and concrete proposals from each group are outlined.

5.1 Group A: Subgrid modeling in canonical incompressible flows

5.1.1 Experiment 1: *Measurements with new instrumentation in all classical canonical flows*

For the purpose of fundamental model development and testing of LES codes and models, there is a serious need for multidimensional data for all canonical turbulent flows (i.e. mixing layers, boundary layers, jets, wakes, homogeneous distorted turbulence, etc.). By multidimensional data, one means data that can be filtered in more than one direction. Such data are currently available only for a very small number of flows under very limited conditions. The data should be assembled by careful experiments performed by several groups (to ensure repeatability) that have access to new-generation experimental tools. Such data are needed for both *a priori* and *a posteriori* analysis. The type of data collected should conform to the general requirements highlighted in the preceding sections. Unaveraged data should be made available, and statistical data should include mean and rms velocities, SGS dissipation, correlation functions, filtered statistics, moments and conditional statistics of the SGS stress tensor and SGS dissipation, higher order moments, etc.

5.1.2 Experiment 2: *Flat-plate boundary layer at high Reynolds numbers to address issues of near-wall modeling at high Reynolds numbers*

This case was also discussed at length in group B and C. See section 5.2 for details.

5.1.3 Experiment 3: *Stagnating channel flow to study effects of distortion and non-equilibrium*

In order to address the problems posed by highly non-equilibrium conditions on subgrid scales and their modeling, a non-canonical flow of non-trivial, but manageable, complexity is proposed.

A fully developed turbulent channel flow impinges upon a perpendicular wall, creating a stagnation region with high mean straining. Figure 2 illustrates the basic geometry.

In order to independently vary the turbulence Reynolds number of the inflow, an active grid can be placed in the channel. This configuration then has an inflow which is fairly easy to control and characterize. Also, it is a flow which may be quite robust with respect to outflow conditions. The geometry should be carefully designed to eliminate the possibility of flow separation. The main goal is to vary the non-dimensional strain parameter Sk/ϵ (S is the strain magnitude) and Reynolds number, Re. A possible variant is to introduce cyclic variations by oscillating the mean mean velocity in the duct, and examining effects of Strouhal number, St. Depending on choices of instrumentation and general constraints, this flow can be implemented in either axisymmetric or planar geometry. Again, the type of data collected should conform

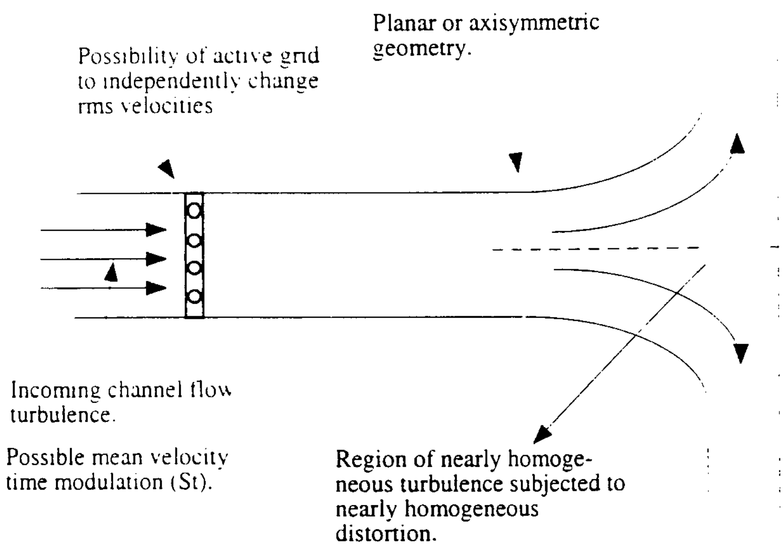

Figure 2: Sketch of flow in a stagnating channel for experiments to probe SGS modeling for non-equilibrium turbulent flows.

to the general requirements highlighted in the preceding sections. Massive planar PIV and selected 3-D PIV would appear to be a particularly useful approach. For reasons explained before, unaveraged data should be made available if at all possible. Statistical data should include mean and rms velocities, SGS dissipation, correlation functions, filtered statistics, moments and conditional statistics of the SGS stress tensor and SGS dissipation, etc.

5.1.4 Experiment 4:*Mixing layer to study how to deal with unresolved thin shear layers and quantify effects of inlet conditions on transition in LES*

A basic experiment in a standard mixing layer is proposed, in which well resolved measurements capture the transition at small scales and the effects of inlet conditions. Inlet and far-field conditions must be very well documented (see section below). The data can be filtered and subgrid-scale stresses computed at various stages of transition. In particular, issues of backscatter of kinetic energy can be studied in this flow. The data can be used to guide model development of unresolved shear layers. For a more detailed discussion of sensitivity to inlet conditions, see section 5.2 below.

5.2 Group B: Specification of and sensitivity to inlet and wall-boundary conditions and Group C: LES in high-Reynolds number flows, especially wall-bounded flows.

Because the issues addressed by groups B and C are interrelated, the results of their discussions will be presented together in this section. General observations drawn from each group will be summarized first, followed by conclusions concerning inlet conditions and wall boundary conditions. Lastly, recommendations regarding experiments in high Reynolds number wall-bounded flows will be discussed. The discussion of inlet conditions (section 5.2.2) is primarily the results of discussions in group B, while the discussions of high Reynolds number experiments (section 5.2.4) is primarily the result of group C discussions.

5.2.1 General Observations

Both groups strongly affirmed the need to develop new wall boundary treatments for LES, and to obtain data at high Reynolds numbers for this purpose. If LES is to enable the simulation of flows with arbitrarily high Reynolds numbers, the filter widths, and therefore the resolution requirements must be independent of Reynolds number for large Reynolds number (see section 3.4). Developing near-wall models in this context that are valid for large Reynolds numbers is the primary challenge in LES near-wall modeling. To support this development, it is essential that data be available at very high Reynolds numbers, especially in view of recent controversies concerning the behavior of high Reynolds number wall turbulence (e.g. George *et al.* 1997; Barenblatt *et al.* 1997).

It was generally agreed that studying canonical flows (boundary layer and channel flow were mentioned specifically) would offer the most insight when developing models due to their universal nature. The goal here is not to confirm LES results, but to support LES modeling development (see section 2.2). These flows offer the additional benefit of experimental simplicity (relative to most non-canonical flows). This reaffirmation of the need for new canonical experiments was one of the principle conclusions of groups B and C. Note that group A also specifically reaffirmed the need for canonical flow experiments (see section 5.1.1).

It was noted that several non-canonical flows would also have features relevant to the problem. Two mentioned specifically were wall-jets and the T-shaped channel, because they introduce strain. A general observation was also made that one can learn about unperturbed systems by introducing perturbations and observing the system response as an "exploratory tool," rather than an application.

5.2.2 Inlet Boundary Conditions

In characterizing what is needed for inlet boundary data (see section 3.5), one needs to explore several different flows, because the sensitivity of different flows to inlet conditions is different. Three simple canonical flows have been discussed for this purpose: 1) a boundary layer, 2) a mixing layer and 3) a wake. Boundary layers have not generally been considered to be particularly sensitive to inlet conditions. But, attempts to simulate boundary layers with synthetic turbulent inlets designed to match single point second order statistics result in an adjustment period in which the turbulence recovers from the artificial inlet conditions. A mixing layer is of course very sensitive to inlet conditions, especially large-scale quasi two-dimensional disturbances, so presumably quite realistic inlet conditions would be required in this flow. Finally wakes appear to be intermediate between the sensitivity of the mixing layer and the relative insensitivity of the boundary layer.

As discussed above, in addition to inlet and velocity field data, each of these flows would need to be well characterized. For example, the free stream turbulence and mean pressure gradients would need to be known.

5.2.3 Wall boundary conditions

To provide data needed for formulation of LES wall boundary conditions, the greatest need is for detailed measurements (as discussed in section 3) in simple canonical wall bounded flows. There are two obvious candidates, a boundary layer and a channel. For the current purposes, there are advantages and disadvantages to both flows. The channel is convenient for computation, since a fully developed channel is homogeneous in the streamwise, as well as the spanwise, directions. Experimentally, a channel is in some ways easier to deal with since one does not need to control streamwise pressure gradients or free stream turbulence, and one can make a global measurement of mean wall shear stress. Boundary layers have the advantage that different pressure gradients can be imposed, to yield a family of wall-bounded flows. Also, it is observed that boundary layer experiments may be less susceptible to side-wall three-dimensionality such as the corner vortices that occur in the channel flow.

Whether a channel or boundary layer is being measured, it needs to be exceptionally well documented. In addition to the velocity field measurements and wall stress measurements discussed in section 3, the global flow environment needs to be well characterized. In a channel, the strength and the effect on the measurement location of corner vortices needs to be measured, and the extent to which the turbulence is actually fully developed (and therefore streamwise homogeneous) needs to be documented. For a boundary layer, inflow data are needed as discussed in section 3.5, and pressure gradient measurements and free-stream turbulence characterization are needed. Finally, if the surfaces are not hydraulically smooth, then the roughness needs to be characterized. As with inflow turbulence, it is not clear what level of detail is needed in the roughness characterization. Clearly, a detailed description of surface elevation as a function of position is sufficient, though perhaps unattainable. A statistical description should suffice, but what this should be is not known. Roughness is particularly relevant at high Reynolds number where it is difficult to achieve true smooth wall turbulence.

To be useful for LES boundary condition studies, channel or boundary layer experiments need to be at sufficiently large Reynolds number for the LES to be meaningful. In this case one is ideally looking for about a decade of log law, which translates, for a channel, to $Re_\tau \approx 10,000$. Interestingly, it was also mentioned (Hunt) that a possible turbulence "transition" point may exist near $Re_\tau \sim 10,000$, making it all the more important to obtain reliable detailed data above this Reynolds number. However, just as important as reaching high Reynolds numbers, is that data be available for a broad range of Reynolds numbers, to assure the generality of near-wall LES models. During the general discussions of turbulence scaling, it was noted that no clear high Reynolds number limit has been observed, nor is there any reason to believe that one should exist. Turbulence may be "fundamentally different" at very high Reynolds numbers, but specific transition points are not established.

5.2.4 High Reynolds Number Wall Turbulence Experiments

A mentioned above, there was broad agreement that wall turbulence experiments should be conducted at Reynolds number high enough to be appropriate for LES. However, the design of such experiments requires great care. In particular, experiments should be designed that will adequately resolve all measurements in order to draw meaningful conclusions. Ten wall unit resolution is adequate to resolve the most important scales of the flow. As Reynolds number increases the smallest scales of the flow get increasingly smaller, making it increasingly difficult to resolve them. Liquids and high-pressure facilities offer high Reynolds numbers but the associated length scales are too small to resolve using known instruments. Instead, high Reynolds number should be achieved through larger scale facilities with gas flows or the atmospheric boundary layer. However, because the atmospheric boundary layer has uncertainties associated with it, a large-scale experimental facility becomes the logical choice, although both types of experiments should be pursued to allow for comparison. The necessity of such a large-scale facility was one of the principal points of consensus of the groups C. A compromise design that uses pressurized gas to increase the Reynolds number by increasing the density can reach very high Reynolds number at scales of only one meter, but instrumental resolution is still a limitation.

One obvious situation in which extremely large Reynolds numbers occur is in atmospheric flows. It was noted that interests in atmospheric flows are often different from those in turbulent flows of engineering interest. For example, the outer region/edge of the boundary layer is of great importance, particularly the instantaneous structure there (intermittency), because of the effects on propagation of acoustic and electromagnetic waves through the atmosphere. When experiments (whether laboratory or atmospheric) are designed to address these issues, they may not address the critical wall-boundary issues in engineering LES. Likewise, channel flow experiments will do nothing to address the outer layer intermittency questions.

However, it should be possible for experimental programs to address both the needs of atmospheric community and the engineering LES community. In particular, facilities for atmospheric boundary layer research, such as the SLTEST facility at the US Army Dugway Proving Grounds (Klewicki *et al.* 1998), provide a wonderful opportunity to make near surface measurements in very high Reynolds number boundary layers.

5.3 Group D: Subgrid modeling for supersonic flows and chemically-reacting flows

As mentioned in Section 2.3, there are a number of additional mechanisms that require modeling in applications of importance; these mechanisms include: chemical reactions, compressibility, multiple phases in flows, system rotation, and stable and unstable stratification. In this section, experiments are suggested for two of these mechanisms, compressibility and chemically-reactions.

5.3.1 Compressible Flows

Compressible flows include lower speed (subsonic) flows as well as high speed supersonic and hypersonic flows. The suggestions in this section will be restricted to experiments and measurements in supersonic and hypersonic flows. The Reynolds-averaged approach to modeling supersonic and hypersonic flows has not been very successful for most quantities of interest, and large-eddy simulation provides some hope of significantly improved modeling.

A series of experiments of increasing complexity is recommended. The measurements suggested are mainly one-point averages, to be used for *a posteriori* testing. The subgrid modeling for supersonic and hypersonic flows is at an earlier stage of development than for incompressible flows, so that more basic information is required. Furthermore, the measurement difficulties in supersonic and hypersonic flows are severe enough to make instantaneous, planar data for *a priori* testing less practical.

Experiment 1: *'one-dimensional' shock/turbulence interaction*

This experiment would involve passing a strong shock (e.g., $\Delta p/p \sim 2$ and higher) through homogeneous grid turbulence (figure 3a). Data of interest are the Reynolds stress tensor and corresponding spectra, and information on shock distortion.

Experiment 2: *'two-dimensional' supersonic flow over a wedge*

This second flow involves a shock/turbulent boundary layer interaction (figure 3b). Data of interest here are the Reynolds stress tensor and corresponding spectra, the heat flux at the boundary and the turbulent heat flux in the flow interior, and the friction coefficient. A major difficulty in applying LES to this flow is that no adequate near-wall model exists. Hopefully the results coming from experiments suggested in Section 5.2 would be helpful here. It is further suggested that lower Reynolds number cases ($Re_\delta \sim O(10^5)$) be included so that the LES could be used for these cases without the need for near-wall models.

Experiment 3: *flow past a 'two-dimensional' inlet*

In addition to including shock/boundary layer interactions, this flow also includes oblique shock interactions (figure 3c). Data of interest are the same as in Experiment 2. Again, in addition to high Reynolds number flows, lower Reynolds number cases would be useful in order to avoid employing a wall function model.

5.3.2 Chemically-Reacting Flows

In reacting flows, the distinction is often made between flows with non-premixed and premixed reactants. In the former, turbulence plays an important role in mixing the reactants. Furthermore, modeling turbulent mixing is important in its own right. Therefore a series of three experiments are suggested, the first addressing turbulent mixing, the second premixed reacting flows, and the final series addressing non-premixed reacting flows.

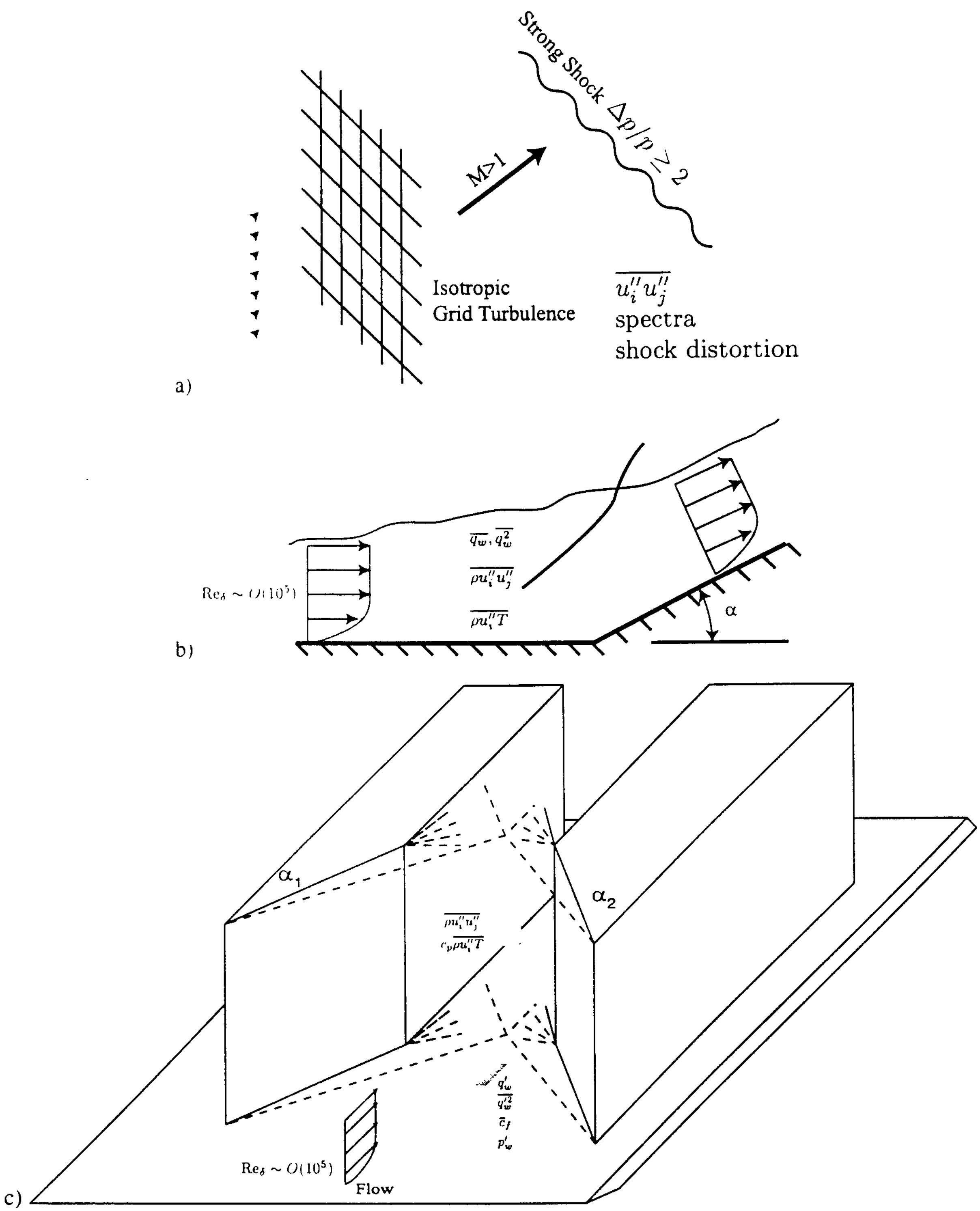

Figure 3: Experimental configurations for shock-turbulence interactions; a) turbulence passing through a normal shock, b) boundary layer turbulence on a compression ramp, c) turbulence in a supersonic inlet.

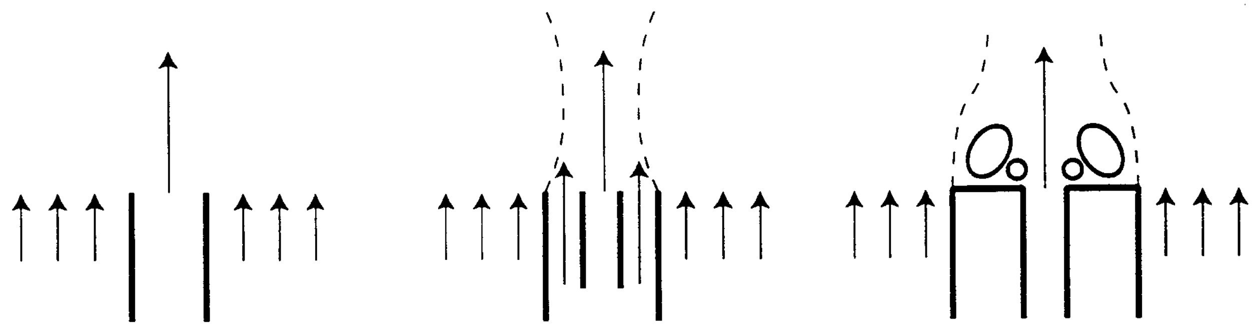

Figure 4: Flows for use in non-premixed chemistry experiments.

Experiment 1: *turbulent mixing*

Most turbulent, chemically-reacting flows are mixing limited, so that modeling turbulent mixing accurately is a necessary condition for the validity of any model. Thus a non-reacting, mixing experiment is suggested, e.g., an axisymmetric jet seeded with a passive scalar (Z). Measurements on two scales are desired. Very local, very high resolution, planar measurements of Z and its dissipation rate χ can be used for *a priori* analysis. Measurements of the scalar statistics across the entire jet can be used for *a posteriori* testing.

Experiment 2: *premixed chemistry*

In premixed chemistry, the important feature is the rate of flame propagation. A series of two experiments is suggested. The first is flame propagation through a premixed, turbulent flow. Of interest here are various aspects of the flame, including the local flame speed and flame surface area. Also, measurements of the turbulence and chemical compositions ahead of and behind the flame are of importance.

The second step in the premixed flame series would be experiments for reactions in a closed container containing premixed species, e.g., a cylinder in a model of an internal combustion (IC) engine. The IC engine is not treated accurately with unsteady RANS, while LES could provide a significant improvement. Both very high resolution, planar measurements are of interest for *a priori* analysis, as well as measurements of phase-averaged quantities throughout the cylinder for *a posteriori* testing.

Experiment 3: *non-premixed chemistry*

There is an on-going, large-scale experimental program which addresses this problem, the International Workshop on Measurement and Computation of Turbulent, Non-premixed Flames. This effort is coordinated at the Sandia National Laboratory in Livermore, California. Much of the laboratory data are available on the workshop WEB-site (*http://www.ca.sandia.gov/tdf/workshop.html*). The experiments were originally aimed at validating RANS models, but more recently some validation work for LES has been initiated. The experiments consist of a series of flows of increasing complexity, with chemistry also of increasing complexity (see figure 4). The experiments range from simple jet flames (H_2/N_2, H_2/He, $CO/H_2/N_2$, $CH_4/H_2/N_2$) to piloted jet flames (CH_4/air, natural gas), to bluff body flames (CH_4/H_2); more recently swirl is being included in some of the flows. There is also some non-reacting flow data available for a propane jet and for bluff-body flows.

Instantaneous line and planar measurements are planned, which could be used for both *a priori* and *a posteriori* testing of LES models. Measurements will be made of scalar gradients: (i) line Raman, Rayleigh or LIF measurements plus two intersecting planes of PLIF; (ii) measurements of conditional scalar dissipation rates ($\chi|Z$), (iii) spatial structure of the reaction zone, and (iv) detailed structure of laminar flames.

Also planned are measurements related to stoichiometric contours: (i) simultaneous CH, OH and PLIF; (ii) flame surface density; and (iii) flame surface curvature and related quantities.

flows. layer is the one. boundary layer, flow should be made included) leave the report "open-ended" links that are being prepared. discussion topics.

6 Conclusions and closing comments

The unique problems posed by LES call for a renewed effort in experimental turbulence research based on new-generation measurement and analysis techniques. In this text we wish to summarize some of the most important issues that were brought forward during the workshop on Turbulence Measurements for LES. One of the most striking aspects of the workshop results is the unanimous assessment that new measurements in classical canonical flows are needed. In particular, basic wall-bounded flows such as a planar channel or flat-plate boundary layer were called out as important by 3 of the 4 workshop discussion groups. It was felt that new measurements are needed in these well studied flows because LES makes special demands on experimental data that cannot be met with existing data. Also, new-generation experimental techniques that can meet the demands of LES are now available and/or are being developed.

It is hoped that the issues and experiments discussed here will stir the interests of both the turbulence research community and the funding agencies. It is clear that allocation of intellectual and financial resources in this general area of fundamental research are needed to realize the great potential of LES for robust and reliable prediction of turbulent flows. Development of such reliable prediction techniques are of great practical importance.

7 Possible points for open discussion on this web page:

This is a "random list" of questions

1. Are there other fundamental flows which would be well-suited for LES developments? Which flows?
2. Are there additional basic issues in LES which could be studied based on experimental data?
3. Are there other statistical quantities upon which comparisons between experiments and LES should be based (besides those mentioned in this text)?
4. What other emerging measurement techniques can be brought to bear on the problem?
5. Should experimental efforts be centralized in a few high-quality facilities or should resources be distributed to a number of different groups?
6. Is it necessary for numerical simulators, modelers, and experimenters to be located in the same institution to foster better integration between the various approaches, or could distant www-based (say) interactions be developed to serve the integrated development efforts?

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Appendix: List of Participants

This appendix includes a list of participants in the workshop and their contact information. Most participants were affiliated with one of the four groups described in section 5, the remainder floated among groups as observers. The group affiliations were as follows:

Workshop Group Participants

Group A	Group B	Group C	Group D
Beutner	Foss	Wark	S. Chen
Meneveau	Moser	Adrian	Riley
H. Chen	Balachandar	Eaton	Andreopoulos
Domaradzki	Bonnet	Hunt	Barlow
Elliot	Brasseur	Klewicki	Ferziger
Glauser	Fasel	Marusic	Givi
Karniadakis	Hussain	Piomelli	Haworth
Katz	Jimenez	Pullin	Knight
Kim	Kerr	Squires	Koochesfahani
Simpson	Saric	Wallace	Schilling
	Wygnanski	Wyngaard	Warhaft

Participant List

Prof. Ron Adrian
TAM Department
University of Illinois
104 S. Wright St.
Urbana, IL 61801
Ph: 217-333-1793
r-adrian@uiuc.edu

Prof. Suresh Aggarwal
Dept. of Mech. Engr.
Rm. 2039, UIC
842 W. Taylor Street
Chicago, IL 60607
Ph: 312-996-2235
ska@uic.edu

Dr. Amy Alving
DARPA Special Projects Office
3701 N. Fairfax Drive
Arlington, VA 22203-1714
703-248-1500
aalving@darpa.mil

Prof. Y. Andreopoulos
Dept. of Mech. Engr.
Convent Ave. & 140th St.
CCNY-CUNY
New York, NY 10031
Ph: 212-650-5206
andre@me-mail.engr.ccny.cuny.edu

Prof. S. Balachandar
Theoretical & Applied Mechanics Dept.
University of Illinois
Urbana, IL 61801
Ph: 217-244-4371
s-bala@uiuc.edu

Dr. Robert S. Barlow
P.O. Box 969
MS 9051
Sandia National Lab.
Livermore, CA 94551-0969
Ph: 510-294-2688
barlow@ca.sandia.gov

Dr. Tom Beutner
AFOSR/NA
801 N. Randolph Street
Arlington, VA 22203
Ph: 703-696-6961
tom.beutner@afosr.af.mil

Dr. J.P. Bonnet
LEA, URA CNRS 191
University de Poitiers
43, rue de l'Aerodrome
F-86036 Poitiers Cedex. FRANCE
Ph: 33-49-537031
bonnet@univ-poitiers.fr

Prof. James Brasseur
Dept. of Mech. Engr.
Penn State University
University Park, PA 16802
Ph: 814-865-3159
brasseur@jazz.me.psu.edu

Dr. Hudong Chen
Exa Corp.
450 Bedford St., Suite 1
Lexington, MA 02173-1520
Ph: 781-676-8512
hudong@exa.com

Dr. Shiyi Chen
CNLS
LANL
Los Alamos, NM 87545
Ph: 505-667-1444
syc@watson.ibm.com

Prof. JA Domaradzki
Dept. of Aero. & Mech. Engr.
RRB 215
University of Southern California
Los Angeles, CA 90089-1191
Ph: 213-740-5357
jad@spock.usc.edu

Prof. J.K. Eaton
Dept. of Mech. Engr.
Bldg. 500
Stanford University
Stanford, CA 94305
Ph: 650-723-1971
eaton@vonkarman.standford.edu

Prof. Peyman Givi
Dept. of Mech. & Aerospace Engr.
334 Jarvis Hall
SUNY-Buffalo
Amherst, NY 14260
Ph: 716-645-2593
givi@eng.buffalo.edu

Professor Gregory Elliott
Mechanical & Aerospace Engr.
Rutgers University
Piscataway, NJ 08854
Ph: 732-445-3282
gelliott@rci.rutgers.edu

Prof. Hermann F. Fasel
Aero. & Mech. Engr.
University of Arizona
Tucson, AZ 85721
Ph: 520-621-2771
faselh@u.arizona.edu

Dr. Joel H. Ferziger
Dept. of Aero./Astro./Mech. Engr.
Stanford University
Stanford, CA 94305-3030
Ph: 650-725-2077
ferziger@ecoule.stanford.edu

Prof. John F. Foss
Mech. Engr. Dept.
Michigan State University
East Lansing, MI 48824
Ph: 517-355-3337
foss@egr.msu.edu

Prof. Mark Glauser
Dept. of Mech. & Aero. Engr.
Clarkson University
266 CAMP
Potsdam, NY 13699-5725
Ph: 315-268-6683
glauser@clarkson.edu

Dr. Daniel C. Haworth
Dept. of Mech. & Nuclear Engr.
Penn State University
University Park, PA 16802
814-863-6269
dch12@psu.edu

Prof. J.C.R. Hunt
DAMTP
Silver Street
Cambridge CB3 9EW
UK
Ph: 44-12-23-337900
j.c.r.hunt@damtp.cam.ac.uk

Prof. Fazle Hussain
Dept. of Mech. Engr.
University of Houston
Houston, TX 77204-4792
Ph: 713-743-4545
fhussain@uh.edu

Prof. Javier Jimenez
Bldg. 500
Center for Turbulence Research
Stanford University
Stanford, CA 94305
Ph: 650-723-9596
jimenez@ctr-iris2.stanford.edu

Prof. George Karniadakis
Dept. of Applied Mathematics
Brown University
Providence, RI 02912
Ph: 401-863-1217
gk@cfm.brown.edu

Prof. Joseph Katz
118 Latrobe Hall
Johns Hopkins University
Baltimore, MD 21218
Ph: 301-338-5470
katz@polaris.me.jhu.edu

Dr. R.M. Kerr
MMM Div.
1850 Table Mesa Dr., Box 3000
NCAR Foothills Lab.
Boulder, CO 80307
Ph: 303-497-8991
kerrobt@ncar.ucar.edu

Prof. John Kim
Mech. & Aero. Engr. Dept.
UCLA
Los Angeles, CA 90095-1597
Ph: 310-825-4393
jkim@seas.ucla.edu

Prof. J.C. Klewicki
Dept. of Mech. Engr.
University of Utah
Salt Lake City, UT 84112
Ph: 801-581-7934
klewicki@baloo.mech.utah.edu

Prof. D.D. Knight
Dept. of Mech. & Aero. Engr.
98 Brett Rd.
Rutgers University
Piscataway, NJ 08854-8058
Ph: 732-445-4464
knight@jove.rutgers.edu

Prof. M. Koochesfahani
Dept. of Mech. Engr.
Michigan State University
East Lansing, MI 48824
Ph: 517-353-5311
koochesf@egr.msu.edu

Prof. Francis Loth
Mech. Engr. Dept.
3047 ERF, UIC
Chicago, IL 60607
Ph: 312-996-3045
floth@uic.edu

Prof. Ivan Marusic
Aerospace Engineering and Mechanics
University of Minnesota
110 Union Street SE
Minneapolis, MN 55455
tel: (612) 625 3566
email: marusic@aem.umn.edu

Prof. Charles Meneveau
Dept. of Mechanical Engineering.
Johns Hopkins Univ.
122 Latrobe Hall
3400 N. Charles St.
Baltimore, MD 21218-2686
410-516-7802
meneveau@titan.me.jhu.edu

Prof. Robert Moser
TAM Department
University of Illinois
104 S. Wright St.
Urbana, IL 61801
Ph: 217-244-7728
r-moser@uiuc.edu

Prof. Ugo Piomelli
Dept. of Mech. Engr.
University of Maryland
College Park, MD 20742
Ph: 301-405-5254
ugo@eng.umd.edu

Prof. D. Pullin
MC 105-50
Caltech
Pasadena, CA 91125
Ph: 626-395-6081
dale@galcit.caltech.edu

Dr. L. Patrick Purtell
ONR, Code 1132
800 N. Quincy Street
Arlington, VA 22217
Ph: 703-696-4405
purtelp@onr.navy.mil

Prof. James Riley
Department of Mechanical Engineering
Box 352600
University of Washington
Seattle, WA 98195
Ph: 206-543-5347
rileyj@u.washington.edu

Prof. William Saric
Mech. Engr. Dept.
Arizona State University
Tempe, AZ 85287-6106
Ph: 602-965-2822
saric@asu.edu

Dr. Oleg Schilling
Hydrodynamics & Turbulence
Theory & Simulation Group
University of California
Lawrence Livermore National Lab.
P.O. Box 808, MS L-22
Livermore, CA 94551
Ph: 925-423-6879
schilling1@llnl.gov

Prof. Roger Simpson
Dept. of Aero. & Ocean Engr.
VTI/State University
Blacksburg, VA 2406-0203
Ph: 540-231-5989
simpson@aoe.vt.edu

Prof. K.D. Squires
Dept. of Mech. & Aero. Engr.
Box 876106
Arizona State University
Tempe, AZ 85287-6106
Ph: 480-965-3957
squires@uvm-gen.emba.uvm.edu

Dr. James Wallace
College of Engineering
University of Maryland
College Park, MD 20742
Ph: 301-405-5271
wallace@eng.umd.edu

Prof. Z. Warhaft
Dept. of Mech. & Aero. Engr.
244 Upson Hall
Cornell University
Ithaca, NY 14853
Ph: 607-255-3898
zw16@cornell.edu

Prof. Candace Wark
ONR, Code 333
800 N. Quincy Street
Arlington, VA 22217
Ph: 703-696-0789
warkc@onr.navy.mil

Prof. I. Wygnanski
Dept. of Aero. & Mech. Engr.
P.O. Box 210119
University of Arizona
Tucson, AZ 85721-0119
Ph: 520-621-2235
wygy@bigdog.engr.arizona.edu

Prof. J.C. Wyngaard
Dept. of Meteorology
Penn State University
University Park, PA 16802
Ph: 814-863-7714
wyngaard@ems.psu.edu

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R. J. Adrian
C. Meneveau
R. D. Moser
J. Riley

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Theoretical & Applied Mechanics at the
University of Illinois at Urbana-Champaign
216 Talbot Lab, 104 S. Wright Street
Urbana, IL 61801

8. PERFORMING ORGANIZATION REPORT NUMBER

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Program Officer Candace Wark ONR
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Arlington, VA 22217-5660

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14. ABSTRACT
This report describes important open issues in Large-Eddy Simulation (LES) of turbulent flows, and points to possible directions for new-generation experimental studies that can address the relevant questions. This report is an outgrowth of a one-and-a-half day workshop held in Chicago in October of 1999 that was funded by NSF, ONR, AFOSR, DARPA and LANL. It contains an introduction to LES and a description of what are currently felt to be the most important pacing items for future developments in LES. It summarizes the type of experimental information that is needed and the new experimental methods that can be brought to bear on the problem. It also proposes several flows that appear well suited to address the important issues identified.

15. SUBJECT TERMS
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